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ABSTRACT

The vortical structures in shear layers govern many dynamic aspects of the jet, including entrainment of mass, transfer of momentum and noise generation. These structures develop from instability waves and undergo a merging process. Vortex merging reduces the time scale and increases the length scale of the shear layer. At the same time pressure fluctuations are induced by the unsteady motion. These pressure perturbations can exert high level dynamic loading on nearby structures, and radiate to the far field as noise. In this study, we examine the generation mechanism of the pressure fluctuations and the radiation process.

I: INTRODUCTION

In the vicinity of a shear layer, pressure fluctuations are produced by the unsteady evolving vortices. Near the flow, the pressure fluctuations are of a hydrodynamic nature. The perturbations propagate in the order of the flow velocity and the amplitude is proportional to the magnitude of the flow velocity. The perturbations can cause high level dynamic loading on a nearby solid surface (e.g. VSTOL aircraft)[1,2] and as a result, structural considerations are required. At the far field, the radiated pressure propagates at acoustic speed. The noise can be a health hazard and can create problems in many practical applications.

The shear layer of a jet is unstable and amplifies the disturbances exponentially[3]. The growing stability waves roll up into large-scale coherent vortical structures which dominate the dynamics of the flow[4]. The structures themselves are not stable and undergo merging[5], an unsteady process which produces noise[6,7] and near field pressure fluctuations[8,9]. The frequencies of the pressure perturbations are the fundamental instability frequency (corresponding to the formation of the primary vortex) and its subharmonics (corresponding to the subsequent vortex mergings).

In jet studies, the flow field[3] and the far field noise[10,11,12] have been extensively investigated. However, information regarding the crucial link, i. e. the near field pressure fluctuations, is very scarce. The present effort is to explore the missing link in order to understand the generation and the radiation of the pressure fluctuations.

This report is a summary of our findings over the past two years[8, 9, 21]. The relation between the generation of fluctuating pressure and the evolution of vortices is clarified first. The modal distributions of the near pressure fluctuation are then determined. Finally, the length scales associated with the transition from the near field to the far field are identified.

II: FACILITY AND INSTRUMENTATION

The jet nozzle has a diameter, D, of 5.08 cm and is connected to the stagnation chamber with a fifth order polynomial contraction. The contraction ratio is 56 : 1. Honeycomb and several layers of screens are used to reduce the background turbulence level to approximately 0.1%. A small angle diffuser connects the stagnation chamber to a 20 cm diameter pipe which leads to the compressed air tanks. The compressed air flows through a dryer before entering five large storage tanks. The operating pressure is regulated by a low noise valve. Extreme care has been taken to remove possible upstream disturbances. Acoustic forcing is provided by eight loudspeakers placed in a cavity near the jet nozzle. The acoustic waves which emit from a thin slit around the nozzle can perturb the thin shear layer in desired manners. The jet is located in an anechoic chamber measuring 7.42 m long, 4.79 m wide and 3.63 m high. The low cut-off frequency is 150 Hz. The chamber is suspended on springs and vibrations higher than 1 Hz are isolated.

The origin of spherical coordinate is defined at the point on the jet axis and five diameter downstream from the nozzle exit. $r = |\vec{r}|$ is the distance away from the origin and β is the angle between $\vec{r}$ and the jet axis. θ is the azimuthal angle.

Multi-channel hot-wires, pressure transducers (Panasonic type wm-32) and microphones (B & K 0.32 cm dia.) are used to record the instantaneous velocity and pressure signals. The data are digitized and processed by a PDP 11-23 microcomputer. The computer is equipped with an ADAC 100 kHz analog-to-digital converter and a SKY array processor.

III: EXPERIMENTAL RESULTS

Preferred Mode and Facility Dependence:

More than a decade ago, Crow and Champagne[13] found that a jet with a top-hat profile was most susceptible to a forcing at a frequency of $f_pD/U_j = 0.3$ which is known as the preferred mode. Since then, a fundamental question has been raised; is the preferred mode a subharmonic of the initial most amplified frequency or a frequency independent of the initial instability? This question was not solved until Kibens[7] performed an experiment in a clean circular jet presumably free of any upstream disturbances. He found that the preferred mode is related to the initial instability in the low speed range and at high speeds has a constant value of 0.44 independent of the initial instability frequency.

Gutmark and Ho[14] conducted a special study of the facility influence on the values of the preferred mode. They found that the residual noise from the facility could cause the values of the preferred mode to change in a stepwise manner rather than remaining constant. Therefore, whether the preferred mode is constant or not can be used as an indication of the cleanliness of the facility. As a matter of fact, the existing data collected over the past two decades have a scatter of 100%, from 0.25 to 0.5, which is presumbly due to the residual noise of individual facilities. In the present facility, tedious trial and error tests and improvements have been carried out until finally, the measured preferred mode over a wide range of velocities has values of about 0.44 (Fig. 1). The data has small scatter but definitely no stepwise behavior. After having achieved this condition, it is believed that the jet is clean and the far field noise as well as the near field pressure fluctuations are free from the influence of the facility.

Sources of Pressure Fluctuations:

Measurements of far field noise [6,7] have shown that the frequencies of the peaks are the same as the initial instability frequency or their subharmonics. The results suggests that the noise sources are fixed in space because there is no Doppler shift. The coherent structures convect in the streamwise direction, but the merging positions are more or less stationary in space [15]. This implies, therefore, that the unsteady motion of the merging vortices produces the noise. In this section, we examine the generation mechanism from the amplitude contours of the near field pressure.

Approximately one thousand measuring stations were used to survey the near field pressure in the vicinity of the jet edge. The jet had a Mach number of 0.088 and was forced at the initial most amplified frequency, f_o. The spectrum at each station was measured. Near the nozzle exit, the spectra have a sharp peak at the most amplified frequency. At downstream locations, the peak at f_o decays as the first subharmonic, f_1, emerges. The grow-decay cycles of f_1, and higher harmonics, f_2, f_3 etc., take place with increasing streamwise distance. The constant spectral density contours can be constructed from the measured spectra and are shown in Fig. 2. The jet edge in the figure is defined as the location where the local mean velocity is five percent of the jet exit speed. The pressure contour map clearly indicates that the pressure perturbations originate from the corresponding vortex merging position. The result is the same as that found in an elliptic jet[16]. The zone of the same pressure intensity increases with decreasing frequency. For example, the 10^{-1} Pa^2/Hz^2 contour covers a narrow region near the first vortex merging position, but extends far from the jet edge for the preferred mode case.

Modal Distribution

The geometrical shapes of the coherent structures have many forms, including axisymmetric rings, helix or other asymmetric configurations. The stability analysis[18,19] shows that the amplification rates of the symmetric mode [mode 0] and the helical modes [mode ± 1] are about the same in the potential core region. The data show that the instability waves intermittently change among the mode 0 and the modes ±1. When the shear layer thickness becomes appreciable, the amplification rate of the helical mode dominates. At the end of the potential core, the mean velocity profile has a bell shape; only the helical mode amplifies[20]. It is expected that the vortex merging process will also be of different modes. It is therefore interesting to investigate the modes of the pressure fluctuations.

Eight pressure transducers are evenly distributed in the azimuthal direction. They are placed in the $\beta = 90°$ plane and r = 10.8 cm, 11.4 cm, 12.1 cm & 15.2 cm. The Mach numbers are varied from 0.12 to 0.58. These transducers are near the end of the potential core and are about two preferred mode instability wavelengths away from the jet edge. Most of the signals are dominated by the pressure generated by the preferred mode. The outputs are Fourier decomposed in azimulthal spatial modes.

The axi-symmetric mode and the helical modes all increase with increasing Mach number, but it is not a strong function (Fig.3). As expected, the +1 mode has the same magnitude as the −1 mode since the jet should have no preferrence regarding the right hand or left hand helix. The magnitude of axi-symmetric mode is higher than the magnitude of each +1 mode or −1 mode, but is about 25% lower than the sum of the +1 modes. This is different from the measurement by Fuchs and Michel[21], which showed that the most dominant mode in their jet was the axi-symmetric mode. Figure 4 shows the changes of the magnitude as a function of the radial distance. The axi-symmetric mode decreases sharply with the distance. Helical modes have much milder variation in the measured range.

The Hydrodynamic Near Field:

Figure 2 shows that the pressure fluctuations decrease rapidly with the distance away from the jet edge. The fluctuating levels in the hydrodynamic region decay exponentially with distance normal to the jet edge and change to algebraic decay in a short distance (Fig. 5). A length scale, $R-R_E$, was defined as a measure of the exponentially decaying region. The scale is determined from the jet edge to the point where the decay curve deviates from the exponential decay line (Fig. 5). The scale at a specific frequency was measured at the streamwise locations where the vortex mergings occur[3,15]. R is the distance measured normal from the jet edge at these streamwise locations. When the scales, $R-R_E$, are normalized to the instability wavelength at the specific frequency $\lambda = U_j/2f$, the normalized values are almost the same for all frequencies and are about half of the local instability wavelength (Fig. 6). Hence, the exponential decay region of the hydrodynamic pressure fluctuations extends only in the order of one instability wavelength away from the jet edge. This result agrees with the measurements made in an elliptic jet.[16]

The Acoustic Near Field:

In the hydrodynamic near field, the length scale is the instability wavelength. At the far field, the length scale has to be the acoustic wavelength. In the low Mach number range, the two length scales are one order of magnitude apart. In other words, there must be another transitional layer between the hydrodynamic exponential decay region and the far field. In order to examine this region, the pressure fluctuations were measured around a chosen location, $r_o \approx 127$ cm. This location is far from the hydrodynamic field but only a few acoustic wavelengths from the source, so that we can explore the transition process. The acoustic wavelength, $\lambda_a(M)$, used here is the wavelength at the preferred mode of a jet at Mach number M. The pressure intensity decreases algebraically with distance in this region as

$$p^2 \sim r^k \qquad (1)$$

The values of k are shown in Fig. 7. At $\beta = 50°$ and $30°$, the values of k vary with Mach number and reach the asymptotic value of −2 at M = 0.74. However, this is not a Mach number effect. It actually indicates that an acoustic near field exists outside the hydrodynamic field, since r_o = 127 cm is about ten acoustic wavelengths from the jet at high Mach number ($r_o/\lambda_a(M)$ = 7.48 at M = 0.75), and is only about one wavelength from a low Mach number jet ($r_o/\lambda_a(M)$ = 1.51 at M = 0.15). The angular dependence can be explained as follows: the long wavelength waves propagate in the direction of small β, at a larger angle, e.g. $\beta = 75°$, the spectrum contains more high frequency wave than that at a lower angle. Therefore, the peak level acoustic waves at larger angles are a few more acoustic wavelengths away than those at smaller angles.

The existence of an acoustic near field can be further substantiated by the measurements of acoustic intensity dependence on the Mach number for $0° \leq r \leq 127$ cm.

$$p^2 = M^N \qquad (2)$$

The values of N are plotted against $r/\lambda_a(M)$ in Fig. 8. It takes about ten acoustic wavelengths to reach the eighth power dependence on Mach number. The low Mach number measurements have low power dependence, $4 \leq N \leq 6$, because of their long acoustic wavelengths. If the set of data is plotted as the parameter of the angle with respect to the jet axis (Fig. 9), a slight angular dependence can be observed especially between $\beta = 30°$ and $75°$.

The traditional acoustic far field is defined at about fifty jet diameters from the nozzle. This scaling is essentialy based upon the length scale of the preferred mode wavelength. Let R_n be the distance from the nozzle to the far field, then

$$R_n / D = 50 \qquad (3)$$

The present experimental results suggest that the proper acoustic far field should be ten $\lambda_a(M)$ away from the jet.

$$R_n / \lambda_a(m) = 10 \qquad (4)$$

or

$$R_n / D = 25 / M \qquad (5)$$

Therefore, Eq. (3) only holds for $M > 0.5$. Eq. (5) indicates that special care is needed for low Mach number jet noise research because a fairly large anechoic chamber is required.

IV: CONCLUSION

The near field pressure contours of a clean jet show that the pressure fluctuations are produced by the vortex merging process. The different geometical configurations of the coherent structures are also reflected in the hydrodynamic pressure fluctuations. The magnitudes of the axi-symmetric mode and the helical modes are of the same order and increase with Mach Number.

Two length scales govern the radiation precess, the instability wavelength and the acoustic wavelength. The hydrodynamic pressure fluctuations extend only about one instability wavelength from the jet edge. It takes ten acoustic wavelengths to reach the acoustic far field.

REFERENCES

1. Yu, J.C., Reddy, N.N. and Whitesides, J.L., "Noise and Flow Characteristics of an Externally Blown Flap", Proc. of Second Interagency Symp. on Univ. Res. in Transportation Noise, 1:219-37, 1974.

2. Ho, C.M., and Nosseir, N.S., "Dynamics of an Impinging Jet", Part I, the Feedback Phenomenon, J. Fluid Mech., 105:119-42, 1981.

3. Ho., C.M., and Huerre, P., "Perturbed Free Shear Layers", Ann. Rev. Fluid Mech., 16:365-424, 1984.

4. Brown, G.L., and Roshko, A., "On Density Effects and Large Structure in Turbulent Mixing Layers", J. Fluid Mech., 64:775-816, 1974.

5. Winant, C.D., and Browand, F.K., "Vortex Pairing, the Mechanism of Turbulent Mixing Layer Growth at Moderate Reynolds Numbers", J. Fluid Mech. 63:237-55, 1974.

6. Laufer, J., and Yen, T.C., "Noise Generation by a Low Mach Number Jet", J. Fluid Mech., 134:1-31, 1983.

7. Kibens, V., "The Limit of Initial Shear Layer Influence on Jet Development", AIAA Paper No. 81-1960, 1981.

8. Ho, C.M., and Lafouasse, B., "Hydrodynamic Pressure Field of an Axisymmetric Jet", AIAA Paper No. 84-2316, 1984.

9. Lafouasse, B., Chan, A., and Ho., C.M., "Near Field Pressure Fluctuations of a Circular Jet", Proc. of IUTAM Symp. on Aero- and Hydro-Acoustics, 1985.

10. Ffowcs Williams, J.E., "Aeroacoustics", Ann. Rev. Fluid Mech., 9:447-68, 1977.

11. Goldstein, M.E., "Aerodynamic Noise", Ann. Rev. Fluid Mech., 16:263-85, 1984.

12. Huerre, P., and Crighton, D.G., "Sound Generation by Instability Waves in a Low Mach Number Jet", AIAA Paper No. 83-0661, 1983.

13. Crow, S.C., and Champagne, F.H., "Orderly Structure in Jet Turbulence", J. Fluid Mech., 48:547-91, 1971.

14. Gutmark, E., and Ho, C.M., "On the Preferred Modes and the Spreading Rates of Jets", Phys. Fluids, 26:2932-38, 1983.

15. Ho, C.M., and Huang, L.S., "Subharmonics and Vortex Merging in Mixing Layers", J. FLuid Mech., 119:443-73, 1982.

16. Gutmark, E., and Ho, C.M., "Near Field Pressure Fluctuations of an Elliptic Jet", AIAA Paper No. 83-0663, 1983.

17. Plaschko, P., "Helical Instabilities of Slowly Diverging Jets", J. Fluid Mech. 92:209-15, 1979.

18. Cohen, J., and Wygnanski, I., "The evolution of Instabilities in the Axisymmetric Jet", Submitted to J. Fluid Mech., 1986.

19. Batchelor, G.K., and Gill, A.E., "Analysis of the Stability of Axisymmetric Jets", J. Fluid Mech., 14:528-551, 1962.

20. Fuchs, H.V., and Michel, U., "Experimental Evidence of Turbulent Source Coherence Effecting Jet Noise", AIAA Paper No. , 1977.

21. Chan, A., Lafousse, B., and Ho, C. M., "Modal Distribution of Pressure Field Generated by a Circular Jet", AIAA PAPER No. 86-1910, 1986.

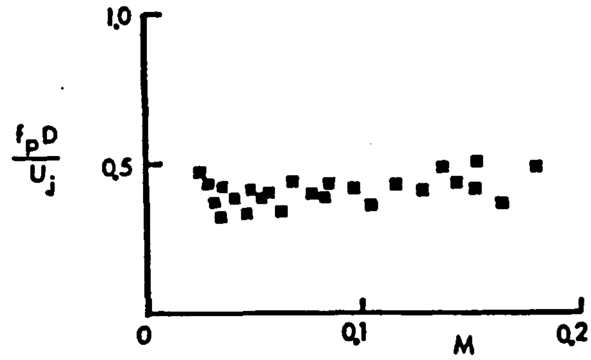

Figure 1: Preferred Mode

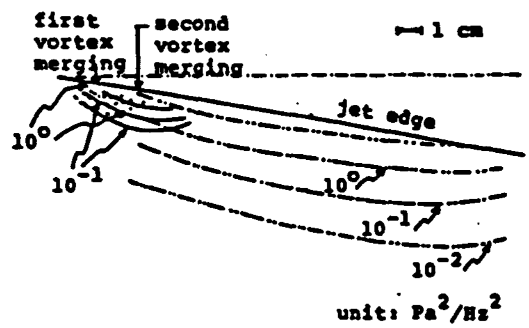

Figure 2: Near Field Pressure Contours

-------- First Subharmonic
——— Second Subharmonic
—··— Preferred Mode

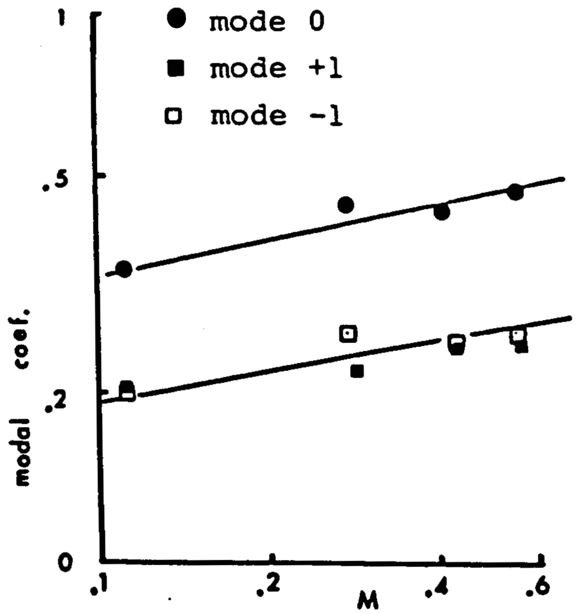

Figure 3: Modal Distribution as a Functions of Mach Number, r = 10.8 cm.

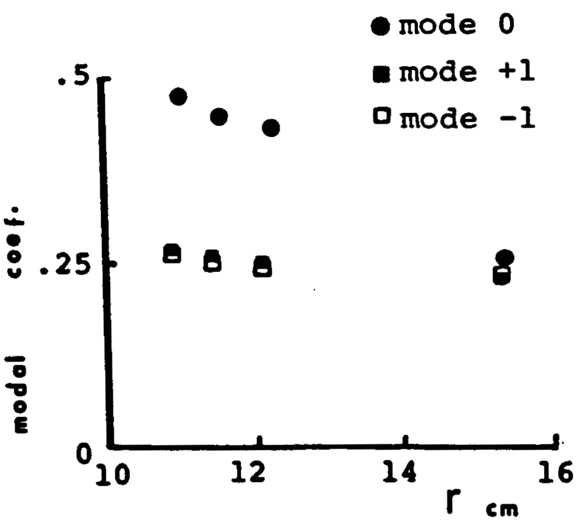

Figure 4: modal Distribution as a Function of Radial Distance, M = 0.58.

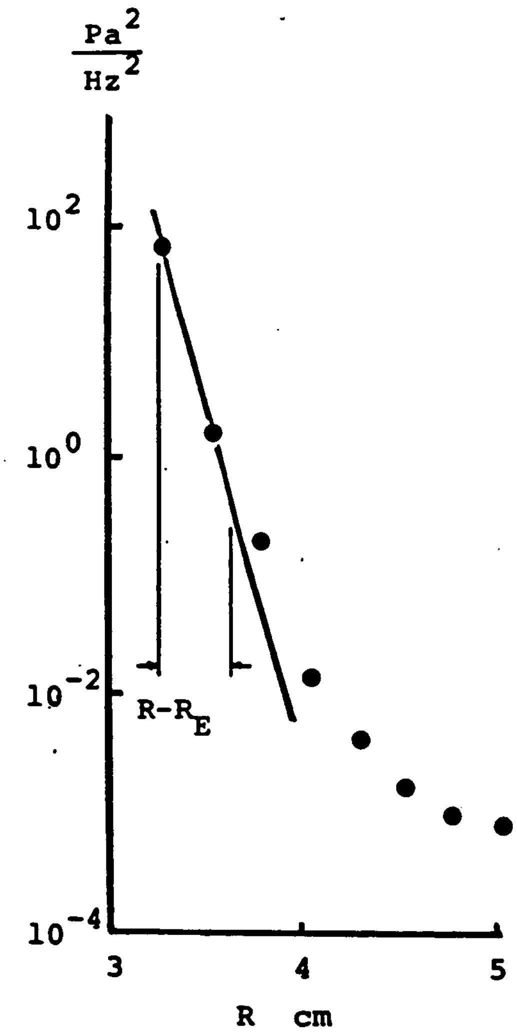

Figure 5: Decay of Hydrodynamic Pressure Fluctuations, M = 0.087, First Subharmonic.

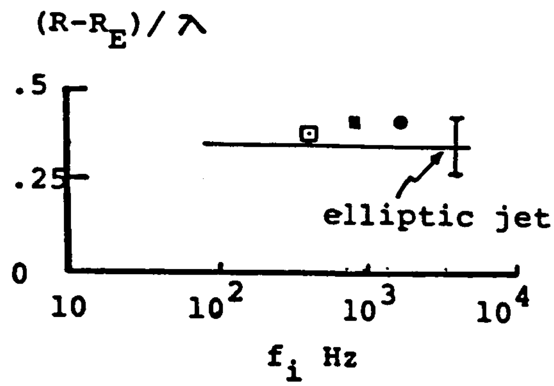

Figure 6: The Normalized Length Scale of Hydrodynamic Near Field, M = 0.087,

- ● f_1: First Subharmonic
- ■ f_2: Second Subharmonic
- □ f_3: Third Subharmonic
- ——— : Data of the Elliptic Jet[16]

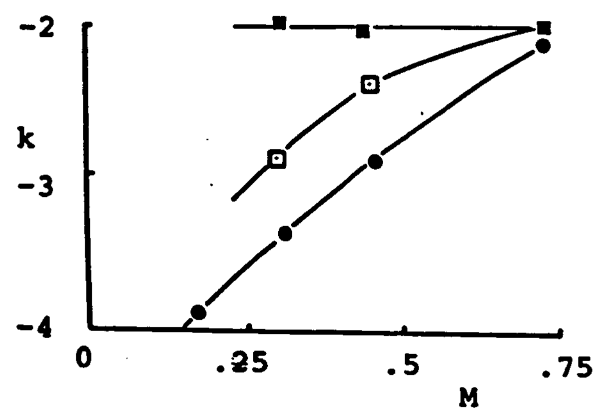

Figure 7: Variation of k with respect to Mach Number,
■ β = 75°, □ β = 50°, ● β = 30°.

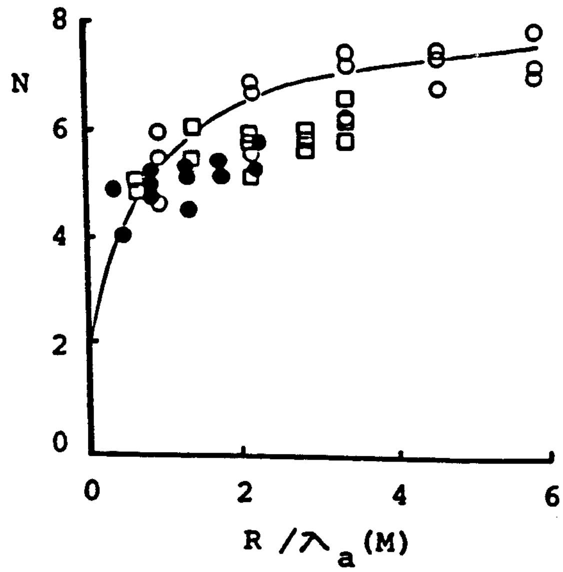

Figure 8: Variation of N with respect to Normalized Distance,
● M = 0.15, □ M = 0.45, ○ M = 0.74.

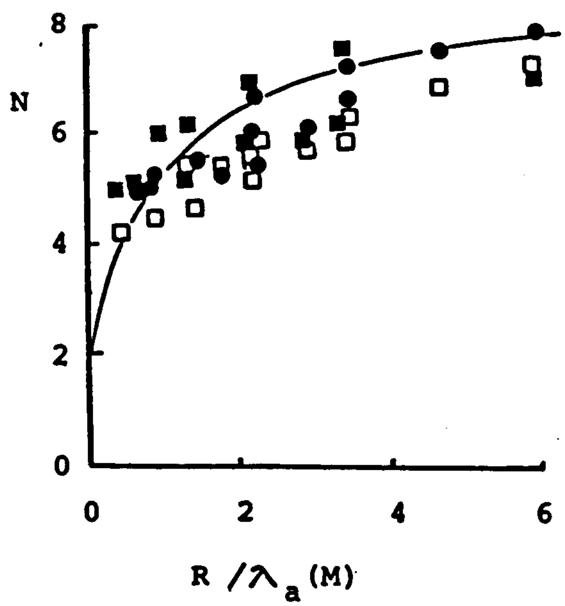

Figure 9: Variation of N with respct to Normalized Distance,
■ β = 75°, ● β = 50°, □ β = 30° .